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Transient stability enhancement of multimachine power systems using nonlinear observer-based excitation controller

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ABSTRACT

This paper presents an approach to design a nonlinear observer-based excitation controller for multimachine power systems to enhance the transient stability. The controller is designed based on the partial feedback linearization of a nonlinear power system model which transforms the model into a reduced-order linear one with an autonomous dynamical part. Then a linear state feedback stabilizing controller is designed for the reduced-order linear power system model using optimal control theory which enhances the stability of the entire system. The states of the feedback stabilizing controller are obtained from the nonlinear observer and the performance of this observer-based controller is independent of the operating points of power systems. The performance of the proposed observer-based controller is compared to that of an exact feedback linearizing observer-based controller and a partial feedback linearizing controller without observer under different operating conditions.

1. Introduction

The effective control or monitoring of power systems requires sufficient information on its states which is uniquely specified by its state variables. However, as in practice on-line measurements of state variables are rarely possible, these unmeasurable state variables are obtained by using state observers. State observers are capable of reconstructing the unmeasurable state variables of a power system from easily available measurements and these observed states can be used as feedback variables for state feedback excitation controllers.

The dynamic behaviors of the observer should be identical to that of the system it observes. If the initial conditions are not set properly or if there are slight disturbances, the model cannot recover fast enough to provide a suitable estimate for control purposes. Moreover, the dynamic elements of the observer need to be faster to achieve an effective estimation. Due to the high nonlinearities in power systems, the observer-based controllers based on linearized power system models are unable to maintain the transient stability following large disturbances because of the far deviations in the dynamic behavior of power systems and designed observers. Therefore, in such a case, nonlinear observers are useful for ensuring the transient stability of power systems.

The dynamic state estimation of power systems using a gain-scheduled nonlinear observer is presented in [1]. However, the main problem associated with the gain-scheduling technique is the adjustment mechanism of controller gains which needs to be pre-computed in off-line and it provides no feedback to compensate for the incorrect schedules. Moreover, the unpredictable changes in the dynamics of a plant may lead to the deterioration of the performance or even complete failures. An observer-based interconnection and damping assignment (IDA) controller overcomes the limitation of nonlinear gain-scheduled observers as the structure and properties of the original state feedback IDA control are asymptotically recovered without introducing a significant deterioration into the performance of power systems [2,3].

Sliding mode observer-based controllers for nonlinear power systems have gained much attention due to their low sensitivity to the plant parameter variations and disturbances which reduces the necessity for exact modeling [4]. In [5], a sliding mode observer-based controller is designed based on a time-varying sliding surface in which the observer is used to estimate the damper winding current. But in practice, the selection of a time-varying sliding surface is a difficult task. A comparison of different advanced state observers is presented in [6] where it is proven that nonlinear extended state observers (NESOs) perform better than sliding mode and high-gain observers. In [6], a NESO is designed based on the transformation of coordinates and in [7], a nonlinear observer for a single machine infinite bus (SMIB) system which

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uses an invariant manifold is proposed. For the design of an observer through a nonlinear manifold, it is essential to determine appropriate mapping which is difficult and the procedure of attaining such mapping is still an open question in the field of nonlinear control theory.

The observer design problem for nonlinear power systems can be solved via a change in coordinates which transforms the system into a different new system and the observer can be designed for the new system. A robust observer-based controller for nonlinear power systems is proposed in [8] in which the power system model is transformed into a linear system using similarity transformations and the parameters of the system are bounded to ensure the stability with parametric uncertainties.

Differential geometric transformation is one of the most useful transformation methods for changing the coordinates of nonlinear systems and is used mainly for designing nonlinear controllers in power systems. Therefore, nonlinear observer-based controllers based on feedback linearization or a combination of feedback linearizing controllers and other observers will be beneficial for power system applications. An observer-based nonlinear excitation controller for power systems is shown in [9,10] where the input–output linearization is used to derive the control law and a sliding mode observer is used to estimate the states with perturbations. In [11], a decentralized nonlinear observer-based adaptive controller for multimachine power systems is proposed which considers nonlinearities in the system and interactions between systems in the form of perturbations. In [11], the control law is derived from feedback linearization and high-gain observers rather than sliding mode observers [9,10] are used and the limitations of high-gain observers can be seen in [6]. Since the differential geometric approach transforms a nonlinear power system model into a linear one, any linear observer design technique for the transformed system will be more practical.

Feedback linearization technique transforms a nonlinear power system into a fully or partly linear one depending on the selection of output functions [12]. If the rotor angle of the synchronous generator is considered as the output, the power system model will be exactly linearized and that of for the speed, the system will be partially linearized. In practice, the measurement of rotor angle is a very difficult task but the speed can easily be measured [13]. Therefore, an excitation controller with speed as a feedback variable will be more effective in terms of practical implementations and providing more damping into the system as this is the derivative of the rotor angle.

The aim of this paper is to design an observer-based excitation controller where the dynamic estimation error of the observer will be minimized by introducing a nonlinear observer gain. The nonlinear gain is calculated based on the partial feedback linearization of the power system model. For the partially linearized power system model, a Luenberger-like observer as presented in [14] is used. Though the controller is designed in a similar way as presented in [15], but states estimated by the observers are used as feedback variables along with other readily available measured variables rather considering some assumptions and transforming into new variables. The performance of the controller is compared with a partial feedback linearizing controllers without any observer [15] and an exact feedback linearizing controller with an observer [16].

2. Power system model and partial feedback linearization

This section is intended to provide an overview of power system model along with some justifications of using partial feedback linearization.

2.1. Power system model

The conventional power systems are equipped large synchronous generators for supplying electric power into the load centers. In a large power system, these synchronous generators are connected with each other through long transmission lines. The characteristics of synchronous generators are complex and to eliminate these complexities some standard assumptions are considered [17]. Normally, a third-order synchronous generator model is widely used for designing excitation controllers [18,19].

If there are N numbers of synchronous generators are interconnected in a multimachine power system via long transmission lines, the third-order electromechanical dynamics of ith machine can be written as [15]

$$\begin{aligned} \dot{\delta}_i &= \omega_i - \omega_{0i} \\ \dot{\omega}_i &= -\frac{D_i}{2H_i}(\omega_i - \omega_{0i}) + \frac{\omega_{0i}}{2H}(P_{mi} - P_{ei}) \\ \dot{E}'_{qi} &= \frac{1}{T_{doi}}(E_{fi} - E_{qi}) \end{aligned} \tag{1}$$

where $i = 1, 2, \ldots, N$, δ_i is the power angle of the generator of ith generator, ω_i is the rotor speed of ith generator with respect to synchronous reference, ω_{0i} is the synchronous speed of ith generator, H_i is the inertia constant of ith generator, P_{mi} is the mechanical input power to ith generator which is assumed to be constant, D_i is the damping constant of ith generator, P_{ei} is the active electrical power delivered by ith generator, E'_{qi} is the quadrature-axis transient voltage of ith generator, E_{qi} is the quadrature-axis voltage of ith generator, T_{doi} is the direct-axis open-circuit transient time constant of ith generator, and E_{fi} is the equivalent voltage in the excitation coil of ith generator.

The relevant algebraic equations that govern the power system operation during the steady-state conditions can be written as

$$\begin{aligned} E_{qi} &= E'_{qi} - (x_{di} - x'_{di})I_{di} \\ P_{ei} &= E'^2_{qi}G_{ii} + E'_{qi}\sum_{\substack{j=1 \\ j \neq j}}^{N} E'_{qj}B_{ij}\sin\delta_{ij} \\ Q_{ei} &= -E'^2_{qi}B_{ii} - E'_{qi}\sum_{\substack{j=1 \\ j \neq j}}^{N} E'_{qj}B_{ij}\cos\delta_{ij} \\ I_{di} &= -E'_{qi}B_{ii} - \sum_{\substack{j=1 \\ j \neq j}}^{N} E'_{qj}B_{ij}\cos\delta_{ij} \\ I_{qi} &= E'_{qi}G_{ii} + \sum_{\substack{j=1 \\ j \neq j}}^{N} E'_{qj}B_{ij}\sin\delta_{ij} \\ V_{ti} &= \sqrt{\left(E'_{qi} - x'_{di}I_{di}\right)^2 + (x'_{di}I_{qi})^2} \end{aligned} \tag{2}$$

where x_{di} is the direct-axis synchronous reactance of ith generator, x'_{di} is the direct axis transient reactance of ith generator, G_{ii} and B_{ii} are the self-conductance and self-susceptance of ith bus, $\delta_{ij} = \delta_i - \delta_j$ is the power angle deviation between ith and jth bus, I_{di} and I_{qi} are direct and quadrature axis currents ith generator respectively, P_{ei} is the real power generated by ith generator, Q_{ei} is the real power generated by ith generator, and V_{ti} is the terminal voltage of ith generator.